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Letter

Solving the problem of anomalous J/ψ suppression by the MPD experiment on the NICA collider[*]

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Abstract. The meassurements of charmonium states production via their decay on lepton pairs by the MPD experiment on the NICA collider at the energies $\sqrt{s_{NN}} = 4$–$11\,\text{GeV}$ per nucleon could provide important data for solving the problem of anomalous J/ψ suppression first observed in central Pb-Pb collisions by the NA50 Collaboration at 158 GeV/nucleon. The anomalous J/ψ suppression could be due to the formation of the QGP in the central heavy-ion collisions. However, this effect could be also interpreted as the result of the comover interactions in nuclear matter. The recent experiments at the SPS, at the RHIC, and the LHC reviewed in this article indicate a more complicated picture of the J/ψ production including the recombination, medium effects, parton shadowing, and the coherent energy loss mechanism. A more simple production mechanism could be expected at low colliding energies. However, no data were obtained at energies below $\sqrt{s_{NN}} = 17\,\text{GeV}$ for heavy-ion collisions. After the short review of the whole set of the data of charmonium states observation the estimation of the production rate for the MPD/NICA is made.

1 Charmonium production at the CERN SPS

The measurement of charmonium states production via their decay on lepton pairs is a useful tool for the investigation of the properties of hot and dense matter created in heavy-ion collisions. The existence of the Quark-Gluon Plasma (QGP) is predicted by lattice QCD at high temperature and large energy density. The dissociation of heavy-quark resonances by color screening in a deconfined medium was suggested by Matsui and Satz as a possible signal of the Quark-Gluon Plasma formation in ultra-relativistic heavy-ion collisions [1].

Charmonium production has been previously studied at the CERN SPS by NA3 [2], NA38 [3], NA50 [4–8], and NA60 [9,10] experiments, at the FNAL [11], and by fixed target p-A experiments at the HERA-B [12]. The production of J/ψ and ψ(2S) has been studied at the CERN SPS by the NA50 experiment. Data have been taken for Pb-Pb collisions at 158 GeV per nucleon [4,8], and for p-A collisions at 450 [5,6] and 400 GeV [7]. The nuclear suppression of the J/ψ production in proton-nucleus reactions and an “anomalous” suppression in central lead-lead collisions were observed [4,8]. In the NA60 experiment the J/ψ production was measured in In-In collisions at 158 GeV per nucleon [9] and in p-A collisions at 400 and 158 GeV [10]. The NA60 results in p-A collisions at 400 GeV confirm the NA50 values of absorption cross section at the same energy. On the other hand, the NA60 158 GeV p-A data give higher values of absorption. The energy dependence of the absorption cross section was observed. However, the older NA3 J/ψ results at 200 GeV [2] give the values of absorption cross section similar to those obtained at the higher energy. This difference has not yet been satisfactorily explained. Therefore, it is important to measure the charmonium production cross sections in different energy domains in p-p and p-A collisions to investigate the energy dependence of cold nuclear matter effects.

The cold nuclear matter effect (CNM) in the suppression of the J/ψ production includes not only nuclear absorption, but also the shadowing effect, *i.e.* the modification of the parton distribution function in nuclear matter compared to the free nucleon. If shadowing is taken into account, the amount of the anomalous J/ψ suppression is reduced. Also, it is necessary to consider the energy loss of partons in nuclear matter. The charmonium can also interact with surrounding comovers and lose energy or even break up.

For In-In collisions at 158 GeV per nucleon after accounting for the effects of cold nuclear matter the additional suppression becomes quite small. But the value of

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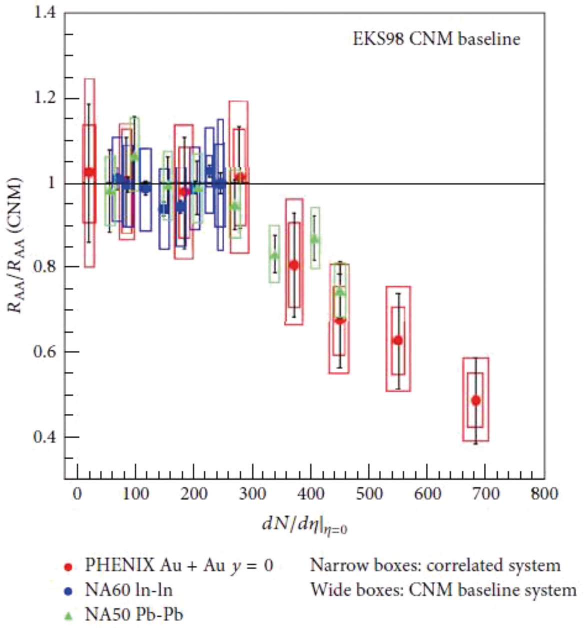

Fig. 1. The $R_{AA}/R_{AA}(CNM)$ ratio obtained at the SPS and PHENIX *versus* $\mathrm{d}N/\mathrm{d}\eta$ at $\eta = 0$.

the anomalous suppression in the most central Pb-Pb collisions is of the order of 20–30%. So, to extract the effects of hot and dense nuclear matter in the J/ψ production the CNM effects and feed-down production from higher charmonium states should be taken into account.

2 Charmonium production at the Relativistic Heavy-Ion Collider RHIC

At the RHIC the production of J/ψ was measured in p-p, d-Au, Au-Au and Cu-Cu collisions by the PHENIX experiment at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ energy in the N-N centre of mass [13–17]. To quantify the suppression of the J/ψ production in heavy-ion collisions the nuclear modification factor R_{AA} was introduced:

$$R_{AA} = \mathrm{d}N_{AA}/\mathrm{d}y \Big/ (\mathrm{d}N_{pp}/\mathrm{d}y \cdot \langle N_{coll}\rangle),$$

that is the ratio of the J/ψ yield in A-A collisions, normalized to the number of binary collisions, N_{coll}, to the J/ψ yield in p-p collisions. The suppression of the J/ψ production in Au-Au collisions is stronger at forward rapidity range $1.2 < |y| < 2.2$ than at mid-rapidity $|y| < 0.35$. The PHENIX data for Au-Au and d-Au collisions were analyzed simultaneously for estimation of the CNM contribution. The nuclear modification factor for cold nuclear matter $R_{AA}(CNM)$ was obtained in Au-Au collisions at the measured rapidity ranges [18]. The ratio $R_{AA}/R_{AA}(CNM)$ estimates the value of additional suppression of the J/ψ production in the hot and dense nuclear matter produced in relativistic heavy-ions collisions. This ratio $R_{AA}/R_{AA}(CNM)$ at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ for Au-Au collisions is similar for the forward and mid-rapidity and reaches about 50% for the most central events and is the same as at the SPS energy [18] (fig. 1).

The production of the J/ψ in asymmetric Cu-Au heavy-ion collisions was measured at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ for both forward (Cu-going direction) and backward (Au-going direction) rapidity [19]. The suppression in the Au-going direction is found to be consistent with the suppression measured in Au-Au collisions. In the Cu-going direction, the J/ψ suppression is stronger. The difference may be due to the CNM effects which are different at forward and backward rapidity. The nuclear modification factor for the J/ψ measured in U-U collisions at $\sqrt{s_{NN}} = 193\,\mathrm{GeV}$ [20,21] is very close to the Au-Au data with a slightly weaker suppression in central U-U collisions.

The nuclear modification factor R_{AA} for the J/ψ production measured in Au-Au collisions at lower energies 62.4 and 39 GeV reveals approximately the same J/ψ suppression as at 200 GeV, but has large statistical errors due to low luminosity and large systematical errors because of the lack of p-p collisions at the same energies [22]. At RHIC the luminosity strongly decreases with decreasing the energy of collisions.

3 Charmonium production at the CERN Large Hadron Collider LHC

At the LHC in four experiments ALICE [23–27], CMS [28, 29], ATLAS [30,31], and LHCb [32] the charmonium productions were measured in different energy, rapidity and transverse-momentum ranges. The charmonium J/ψ and ψ(2S) productions were measured in p-p collisions at 2.76, 7 and 8 TeV and in Pb-Pb collisions at 2.76 TeV. There is a good agreement for p-p collisions between the data obtained by ALICE [23], CMS [28], ATLAS [29] and LHCb [33] experiments in the same kinematic domains [34]. The contribution of B-decay to the J/ψ production cross section was measured. This contribution depends on rapidity, it increases with the growing of J/ψ transverse momentum and is of the order of 10% for transverse momentum about 1.5 GeV/c [28,30,35].

ALICE [24,26], CMS [29] and ATLAS [31] experiments have measured charmonium productions in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$. A smaller suppression was found in the ALICE measurements of the inclusive J/ψ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ [24, 26] compared to PHENIX results in Au-Au collisions at $\sqrt{s_{NN}} = 0.2\,\mathrm{TeV}$ [14]. These measurements are compatible with a regeneration mechanism. This additional, hot nuclear matter effect, works in an opposite direction to the suppression by color screening. The comparison of PHENIX and ALICE nuclear modification factors R_{AA} for inclusive J/ψ production [14,24] is shown in fig. 2.

At the LHC charmonium productions were measured in p-Pb collisions at the energy $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$ by ALICE [26,27] and LHCb [32] experiments. The inclusive J/ψ production has been studied by ALICE [26]. At forward rapidity, corresponding to the proton beam direction, a

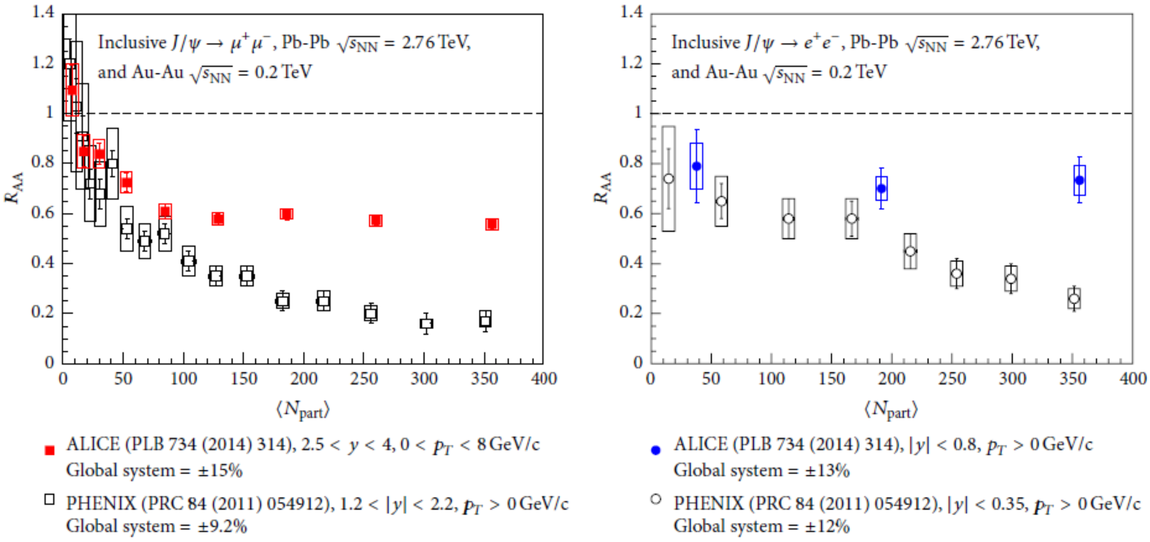

Fig. 2. Comparison of the R_{AA} modification functions, obtained by PHENIX and ALICE experiments. The two panels show the data at forward rapidity (left panel) and mid-rapidity (right panel).

Table 1. Luminosity, cross sections, and counting rates for J/ψ production.

System	$\sqrt{s}$, GeV	σ_{NN}, nb	E, GeV	$B \cdot \sigma_{AA}$, μb $= (A^{0.92})^2\ B \cdot \sigma_{NN}$	L, cm^{-2}s^{-1}	Rate, h^{-1}
Au-Au	9	2.6	42.2	2.57	$1 \cdot 10^{27}$	9.3
Au-Au	11	24	63.6	23.8	$1 \cdot 10^{27}$	86

suppression of the J/ψ yield with respect to binary-scaled p-p collisions is observed, but in the backward region no suppression is found. The Color Glass Condensate (CGC) model [36] could not describe the data. Theoretical calculations based on nuclear shadowing [37] as well as on the models including, in addition, a contribution from partonic energy loss, [38,39] are in better agreement with the experimental results.

The ALICE results are in agreement with results for inclusive J/ψ mesons presented by the LHCb Collaboration [40]. Nuclear modification factors are determined separately for prompt J/ψ mesons and for J/ψ from B-hadron decays by the LHCb experiment. The suppression of prompt J/ψ mesons in p-Pb collisions with respect to p-p collisions at large rapidity is observed, while the production from B-hadron decays is less suppressed.

The ψ(2S) production was measured in p-Pb collisions by ALICE [27]. A significantly larger suppression of the ψ(2S) compared to the inclusive J/ψ was obtained. Theoretical models, which include parton shadowing and coherent energy loss mechanism reproduce J/ψ data, but underestimate the ψ(2S) suppression [39]. For interpretation of the results additional effects should be considered.

At the LHC and RHIC collective and hot nuclear matter effects may also be present in p-Pb at 5.02 TeV and in d-Au collisions at 200 GeV. Therefore, the measurement of nuclear effects at lower energies, where the absence of the QGP formation in p-p and p-A collisions is assumed, give a reference for the study of hot nuclear matter effects. Moreover, the contribution of recombination process is small at low energies. The RHIC heavy-flavor program with the energy scan could perform this investigation but, unfortunately, the luminosity at RHIC strongly decreases with decreasing the energy of collision.

4 Charmonium production at the NICA MPD

It is very important to study the mechanism of charmonium production in heavy-ion collisions at low energy for the investigation of the medium effects and conditions of the Quark-Gluon Plasma formation. We assume that the explanation of anomalous charmonium states suppression could be found at the NICA energy range. It is also planned for SIS300 at FAIR, but it is not possible at SIS100, where charmonium production is below threshold for heavy-ion experiments. At the CERN SPS the fixed target experiment CHIC (Charm in Heavy-Ion Collisions) for charmonium study at energies up to $\sqrt{s_{NN}} \sim 20$ GeV is under preparation [41]. The Beam Energy Scan (BES-I) program at RHIC was performed by STAR and PHENIX collaborations. At STAR there is an ongoing fixed-target program, with data already taken in the gold target test during 14.5 GeV Au-Au run in 2014 with $\sqrt{s_{NN}} = 3.9$ GeV [42], but the luminosity for measuring charmonium production is insufficient. If it would be possible to use the proton and ion beams at the LHC with fixed targets, data with good statistic in the energy interval between the top energy of the SPS ($\sqrt{s} \sim 29$ GeV) and the nominal RHIC energy ($\sqrt{s_{NN}} = 200$ GeV) in p-A and A-A collisions could be obtained [43,44]. The target in the form of a thin ribbon could be placed around the main orbit of the LHC, as it was suggested in [43]. The fixed-target experiment AFTER at the LHC beams by using part of the beam extracted with a strong crystalline field was proposed [44]. The experiment AFTER has a wide physical program and gives the possibility to use different targets with high thickness so it gets high luminosity.

The feasibility of measuring the charmonium production at the energy SIS300 of the FAIR project was previously studied in di-electron decay [45] and in di-muon decay [46]. For Au-Au central collisions the multiplicity of the J/ψ production per event calculated in Hadron-String-Dynamics (HSD) transport model [47] at the 25A GeV beam energy amounts to 1.92×10^{-5} and 5.95×10^{-5} at 35 A GeV energy. The background was calculated in the UrQMD model.

The measurements of charmonia states production in heavy-ion collisions at the MPD NICA [48] at $\sqrt{s_{NN}} =$ 4–11 GeV is in the region, where the baryon density at the freeze-out is expected to be the highest. In this energy range the system has a maximal space-time volume in the mixed quark-hadron phase (the phase of coexistence of hadrons and Quark-Gluon Plasma). The luminosity at the NICA will be higher than the luminosity at the RHIC at the same low energy. It is planned to study charmonium production in p-p up to $\sqrt{s_{NN}} = 29\,\mathrm{GeV}$, in light-ions collisions up to $\sqrt{s_{NN}} = 14\,\mathrm{GeV}$ and in Au-Au collisions up to $\sqrt{s_{NN}} = 11\,\mathrm{GeV}$.

The production cross section $\sigma_{NN}(\mathrm{J}/\psi)$ at $x_F > 0$ is of the order of 1.3 nb at $\sqrt{s_{NN}} = 9\,\mathrm{GeV}$ and of 12 nb at $\sqrt{s_{NN}} = 11\,\mathrm{GeV}$ [49]. These values are close to the HSD model estimates. The branching ratio $B_{ee}(\mathrm{J}/\psi) = 5.94 \times 10^{-2}$. For the realistic estimation of the J/ψ yield in heavy-ion collisions the J/ψ suppression in nuclear matter as $A^{0.92}$ [5–7] was taken into account. The estimates of the counting rate for Au-Au collisions in the table 1 are made for the beam luminosity $L = 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. For full x_F interval the charmonium yield will be two times larger in the case of symmetrical distribution in the barrel geometry. To calculate the numbers of detected charmonia the geometrical acceptance and pair reconstruction efficiency should be taken into account. The $\psi(2\mathrm{S})$ production rate will be 10 times smaller.

At present there are no data for charmonium production in heavy-ion collisions at the energies below 158 A GeV ($\sqrt{s_{NN}} = 17.2\,\mathrm{GeV}$). The data on the J/ψ and $\psi(2\mathrm{S})$ production at NICA energies, will give the possibility to clarify the mechanism of production, to investigate the possibility of charmonium melting in the Quark-Gluon Plasma or absorption on comovers [47], because in this energy range the different dissociation processes could be well distinguished.

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